Novel Acoustic Scattering Processes for Target Discrimination

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LONG TERM GOALS

This is part of the Shallow-Water Autonomous Mine Sensing Initiative (SWAMSI) to improve the reliability of acoustic methods using a wide frequency range and scattering data not necessarily limited to monostatic signatures.

OBJECTIVES

The objective of this grant is to examine issues supportive of the SWAMSI team effort by improving the understanding of acoustic scattering processes relevant to MCM and the shallow water environment. The current emphasis is on the interpretation of bistatic synthetic aperture sonar and acoustic holographic images, the space-time-evolution of bistatic signatures, and on the spectral properties of the scattering. Other objectives involve improved understanding and modeling of scattering mechanisms.

APPROACH

A multifaceted research approach appears to be advisable because some acoustic strategies may not *always* be applicable and different strategies may require widely different amounts of time to acquire the needed data for a given potential mine field. Consequently it appeared to Marston that the SWAMSI program should retain research components that support both low frequency and high frequency sonar technologies.

Beginning in FY07, the experimental effort at WSU began to emphasize scaled targets directly relevant to the planing and interpretation of experiments carried out at the NSWC-PCD pond in cooperation with a team of researchers from the UW-APL. Thus, as explained in the Annual Report for FY07 [1], measurements at WSU were extended to include bistatic and monostatic acoustic properties of solid aluminum cylinders in the free field and adjacent to interfaces. This kind of target was selected because experiments at the NSWC pond in 2007 and 2008 have used aluminum cylinders of various dimensions. Furthermore, scattering by an aluminum cylinder has become a test case for development of finite element methods for the evaluation of both free field scattering and scattering by targets adjacent to an interface [2]. In support of those efforts the experiments at WSU have been concerned with frequency domain ("acoustic color") displays of the scattering as well as time domain and spatial SAS and holographic imaging displays. Beginning in FY08, measurements in the scattering by tilted aluminum cylinders were extended to include low-frequency (low k*a*) features by fabricating targets that were sufficiently small in size. We demonstrated at WSU that elastic modes of tilted aluminum cylinders produce strong scattering for k*a* as small as 1 during initial investigations of this region. The investigation is not limited to the low k*a* region, however, because measurements of

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the scattering from aluminum cylinders with k*a* as small as 10 show prominent features in the scattering associated with elastic waves guided by the surface of the cylinder. Those features would not be present if it were possible to replace the cylinder by a rigid cylinder and may be referred to as elastic glints. Such features remain evident in the scattering by aluminum cylinders for k*a* as large as 30. Research into low-frequency modes of tilted aluminum cylinders was immediately applied at WSU to the investigation of scattering of evanescent waves by elastic cylinders [3].

In addition to understanding scattering effects associated with the elastic response of the target and modifications of the scattering associated with the proximity to an interface, the research during FY08 was extended to examine the potential advantages of bistatic scattering associated with simple specular reflection from the outside of cone-shaped targets having a vertical symmetry axis.

In addition to supporting K. Baik (who left the program after completing his Ph. D. thesis [4] for his current postdoctoral position at ISVR, University of Southampton, UK), the grant provided partial support for the current Doctoral candidate, Jon La Follett, and for a Masters candidate, Anthony Smith. The grant also provided partial summer support for the following undergraduate research assistants: Neil Tauzon and Matt D'Asaro. The grant also provided partial support for the following researchers who assisted in computational tasks: Dr. David B. Thiessen and (during summer 2008) Dr. Nicholas R. Cerruti, a WSU Physics Instructor experienced in acoustics. Thiessen and Cerruti primarily worked on upgrading our FEM based computations.

WORK COMPLETED

In addition to research outlined below in the Results section, the following are noteworthy: Baik's manuscript on the modeling and measurement of the scattering by a partially exposed cylinder (initially supported by grant N000140310583) was accepted for publication [5]; a manuscript on evanescent waves, with OASES calculations by S. F. Morse (partially supported by this grant) was also accepted [6].

RESULTS

(1) <u>Bright helical wave features in free field bistatic scattering by tilted aluminum cylinders</u>: in the report for FY07 [1], Figures 2-4 showed bistatic data and SAS and holographic images in which some of the features were attributed to helical Rayleigh waves on the cylinder. Those waves appeared to radiate sound in such a way that the sound was received by the scanned bistatic hydrophone. In addition, helical wave features were present in the backscattering, Fig. 5 of [1]. During FY08, Baik analyzed the timing and positions of bistatic helical wave features for tilted aluminum cylinders. He also identified other elastic features present in the scattering and in bistatic SAS and holographic images [7]. Some of those new features are associated with the ends of each cylinder. See Chapters 6 and 7 of Baik's thesis [4].

(2) <u>Frequency spectrum of the backscattering by tilted aluminum cylinders -- Free field measurements and analysis of coupling conditions</u>: Baik worked out a procedure for normalizing the scattering data in such a way as to suppress possible biases introduced by the measurement system. He applied this method to backscattering by an aluminum cylinder having a length-to-diameter aspect ratio L/D = 5. To identify the coupling conditions for waves guided down the axis of the cylinder he applied a method of analysis, previously applied by Marston et al [8] to steel cylinders and shells, to the case of

an aluminum cylinder [4]. This method gives the tilt angle γ associated with coupling of sound with elastic modes on an infinite cylinder. The coupling conditions are associated with a mode azimuthal index n = 0, 1, 2, … where n = 0 is associated with a radial (breathing) mode that propagates axially, n = 1 is for what at low frequencies becomes a bending mode of a rod, etc. These dispersion relations were confirmed by overlaying the coupling conditions with exact calculations for the scattering by an infinitely long tilted aluminum cylinder. These results were also used to explain some of the coupling loci evident in backscattering measurements for a cylinder with L/D = 5 as shown in **Figure 1**. In addition some of the important features or "elastic glints" present in the scattering are identified as follows: Above about $ka \approx 10$ ($f \approx 125$ kHz), the measurements show a feature with $\gamma \approx \gamma_R$ where $\gamma_R \approx 30°$ is the angle of incidence associated with the excitation of a Rayleigh wave on a flat elastic half-space in water. The coupling loci are also shown for several of the axial modes. They become nearly degenerate (having similar axial velocities) above $ka = 10$. These modes are superposed to generate a wave similar to a Rayleigh wave which propagates down the meridian of the cylinder and reflects off of the end. Also present for k*a* greater than 14 ($f > 175$ kHz), is a broad enhancement associated with a face-crossing ray [9]. These features have recently been reproduced by K. Williams [2] and D. Burnett [2] in FEM computations of the scattering. These features are also present in NSWC-PCD pond measurements of the scattering by aluminum cylinders.

(3) Modification of the spectrum for backscattering by tilted elastic cylinders as a consequence of the proximity to a flat surface: One of the important issues in the development of MCM based on the frequency spectrum of targets is to improve the understanding of how proximity of the target to a surface alters the spectral features. One approach to advancing this understanding is to investigate the scattering by aluminum cylinders adjacent to surfaces and to compare the results with FEM calculations. LaFollett has been collecting data in scaled tank experiments at WSU pertaining to a special case that is useful for verifying the proper operation of FEM codes: scattering by a tilted cylinder adjacent to a free surface with near grazing incidence. Data is being supplied to APL-UW. For the special case of a broadside cylinder, some of the spectral modifications can be explained using Baik's analysis of rigid cylinder scattering [5,10].

(4) SAS image features from elastic glints for cylinders near flat surfaces: In NSWC pond experiments in 2007 and 2008, monostatic SAS images of tilted cylinders viewed typically with a grazing angle near 20° exhibit bright features for a range of azimuthal orientations of the cylinder. While these features are present for cylinders away from and on the bottom, the image structure is more complicated when the cylinder is on the bottom. The strongest features are close to the back end of the tilted cylinder in the images. Measurements and monostatic SAS images by La Follett at WSU using scaled aluminum cylinders reveal that these features are associated with meridional and helical guided elastic waves that reflect off the cylinder's end and subsequently radiate sound [11]. **Figure 2** shows an example of an image for a tilted cylinder close to a free surface. The features are also evident when plotting the compressed backscattering as a function of time and of the transducer position. LaFollett has also studied and modeled how the features evolve as a function of the distance of the cylinder from the interface. For a cylinder close to the interface the relevant rays are shown in **Figure 3** where, in the case of an aluminum cylinder, the guided waves correspond to Rayleigh waves. The identification of rays with specific features has been verified by studying the evolution of image features as a function of target distance from the interface.

(5) Advantage of bistatic sonar for classification of conical targets -- Ray analysis and optical verification: If sound reflected from the sides of a conical target is to be detected with intermediate-to-

high frequency backscattering, it can be necessary for the grazing angle of the platform to be large. Consequently when large stand-off distances are required, it may be necessary to depend on the shape of acoustic shadows in sonar images. That may be unreliable depending on environmental factors. From this concern, and other considerations, it appears appropriate to understand the potential advantages of bistatic or multistatic sonar systems in which the source and receiver can be at different locations. With this in mind, Marston analyzed the pattern of geometric reflections from the sides of a cone [12] (research supported in part by grant N000140810024 and a collaboration with APL-UW). He also extended this analysis to include the additions to the pattern of rays introduced by interactions between the bottom and the cone. An important result is that bistatic measurements allow specular reflections to be detected with small grazing angles of illumination when using bistatic receivers having large stand off distances. To test this analysis in the optical limit, a graduate student (A. Smith) and an undergraduate assistant (M. D'Asaro) measured light scattering patterns for a small conical mirror placed on a flat mirror illuminated by a laser beam. To record the optical pattern a white projection screen was placed in a plane so as to intersect the reflected rays. The screen was photographed to show the scattering pattern. Records of this type were carried out for a range of laser beam grazing angles. The measurements confirm Marston's analysis. **Figure 4** shows an example of the pattern for near forward scattering.

(6) Bistatic specular reflection from a cone -- acoustic measurements: With the joint support of this grant and N000140810024, LaFollett confirmed the importance of conic bistatic specular reflections in acoustic signatures taken at WSU. In his experiments a cone penetrated the top surface of a tank of water. The cone had a radius *a* of 25 mm, measured at the tank's free surface. For the purposes of this experiment, reflections from the free surface are analogous to reflections from the sea bottom. **Figure 5** shows the time signature as a function of hydrophone position for illumination with a short 275 kHz tone burst with a grazing angle of 21.5°. The corresponding k*a* for the base of the cone was 29. The hydrophone was scanned along a line at a constant depth where the line was selected to intersect the predicted specular reflection pattern for the cone. In each case of an intersection there is a bright feature in the record. In addition to bright features from the cone there is a bright feature from the direct free surface reflection of the incident wave. This type of measurement was done for horizontally scanned hydrophones at different depths. Observed features tend to support the geometric predictions. It is noteworthy that monostatic specular reflection from a frustum (a truncated cone) was previously demonstrated at WSU [4] so that it is anticipated that bistatic measurements with a frustum will yield similar support for the ray theory.

(7) Time-domain analysis of broadside reflections by a cylinder breaking-through (or adjacent-to) a flat surface: We advanced our understanding of the time-domain response of a rigid circular cylinder breaking through a flat surface with grazing broadside illumination by an acoustic impulse. For that case, Baik was able to evaluate the approximate backscattering impulse response as a function of the amount of exposure of the cylinder. This was done by numerical Fourier transformation of his approximations for the scattering amplitude in the case of two-dimensional scattering by an infinite cylinder. That analysis uses the Kirchhoff approximation and is limited to a sub-class of contributions to the scattering in which reflections off-of the curved surface of the cylinder only occur once [5]. The resulting time-domain features evolve in time and magnitude as a function of the amount of exposure of the cylinder and of the grazing angle of the illumination. Baik showed that the time evolution of the bright features as a function of the amount of exposure of the cylinder could be explained by a direct geometrical analysis of reflection by the cylinder and diffraction where the cylinder contacts the interface. See Figures 3.14-3.18 of Baik's thesis [4]. During the experiments at the NSWC pond in March 2008, La Follett was able to demonstrate that this type of geometric analysis could be used to

explain features in the backscattering and the SAS image of an aluminum cylinder suspended close to the bottom of the pond.

(8) Participation in NSWC-UW(APL) experiments at the NSWC-PCD pond: For the status of the analysis of those experiments, see e.g. reports from UW(APL).

(9) Scattering of acoustic Bessel beams by a sphere: Thiessen used comparisons with Marston's analytical results of the scattering of a Bessel beam by a sphere to extend FEM capabilities [13]. Marston analyzed the scattering of a helicoidal Bessel beam by a sphere and showed that the forward diffraction peak is completely suppressed when the sphere is on the beam axis [14]. He also found that illumination of a shell by a helicoidal beam could cause the scattering at certain angles to increase. This work was partly funded by N000140810024.

IMPACT/APPLICATIONS

Detection and analysis of bistatic specular reflection from conical targets may be useful for target classification with mid-to-high frequency sonar even if the stand-off distance is large. For metallic cylindrical targets our data on the spectrum of the scattering has been useful in the testing of FEM codes and in the planning and interpretation of NSWC-PCD "pond" experiments. Our ray analysis of the elastic response of cylinders has been helpful in the interpretation of SAS images from those experiments. Our results may be helpful in the planning of other large-scale tests. Our measurements suggest that high-frequency as well as low-frequency acoustic signatures contain useful information about elastic properties cylindrical targets.

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[13] P. L. Marston, to be presented to the ASA (Miami, Nov. 2008).

[14] D. B. Thiessen & P. L. Marston, “Scattering by a sphere illuminated by a Bessel beam: finite elements modeling (A),” J. Acoust. Soc. Am. 122, 3034 (2007).

[15] P. L. Marston, “Scattering of a Bessel beam by a sphere: II. Helicoidal case and spherical shell example,” accepted in J. Acoust. Soc. Am.

PUBLICATIONS

K. Baik & P. L. Marston, “Kirchhoff approximation for a cylinder breaking through a plane surface and the measured scattering,” IEEE J. Oceanic. Eng. [accepted, refereed].

C. F. Osterhoudt, D. B. Thiessen, S. F. Morse, & P. L. Marston, “Evanescent acoustic waves from subcritical beam illumination: laboratory measurements near a liquid-liquid interface,” IEEE J. Oceanic. Eng. [accepted, refereed].

P. L. Marston, “Scattering of a Bessel beam by a sphere: II. Helicoidal case and spherical shell example,” J. Acoust. Soc. Am. [accepted, refereed].

Kyungmin Baik, *Acoustical Scattering from Cylinders and Other Objects: Short-Pulse Signatures, Bistatic Synthetic Aperture and Holographic Imaging, and Interfacial Scattering Contributions* (Ph. D. Thesis, Washington State University, Pullman WA, May 2008).

HONORS/AWARDS/PRIZES

Philip L. Marston received the 2008 Distinguished Faculty Award, College of Sciences, Washington State University.

Jon La Follett was selected for a two-year term as the Physical Acoustics Representative on the Acoustical Society of America Student Council.

Best Student Paper in Structural Acoustics and Vibration Award (December 2007 ASA meeting) for K. Baik, C. Dudley, & P. L. Marston, “Tilted aluminum cylinder acoustic scattering properties and holographic and SAS images.”

Second Place Best Student Paper in Underwater Acoustics (July 2008 ASA meeting) for J. La Follett, K. Baik, & P. L. Marston, “Elastic and interfacial contributions to SAS images of tilted metal cylinders: Laboratory experiments.”

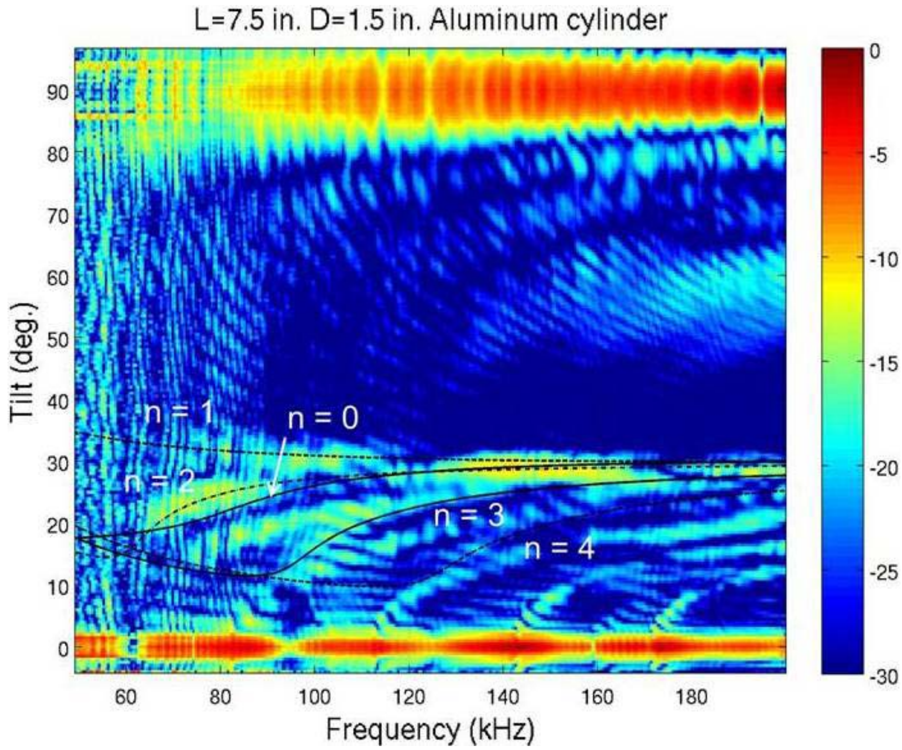

Figure 1. Spectrum of the backscattering by a tilted aluminum cylinder in water. The horizontal axis is frequency and the vertical axis is the tilt angle. The tilt angle is 0° for broadside and is 90° for end-on illumination. A color dB scale shows that the displayed dynamic range is 30 dB. Superposed on the measurements are calculated mode-coupling curves [4] where the mode shape is indicated by the index n. The bright patch near 30° and 125 kHz is the onset of an elastic wave that runs down the meridian of the cylinder. The bright patch near 60° and 180 kHz is from an elastic face-crossing ray. The diameter of the cylinder is 38 mm and the length/diameter aspect ratio L/D is 5. For related time-domain measurements, see Figure 5 of the report for FY07 [1].

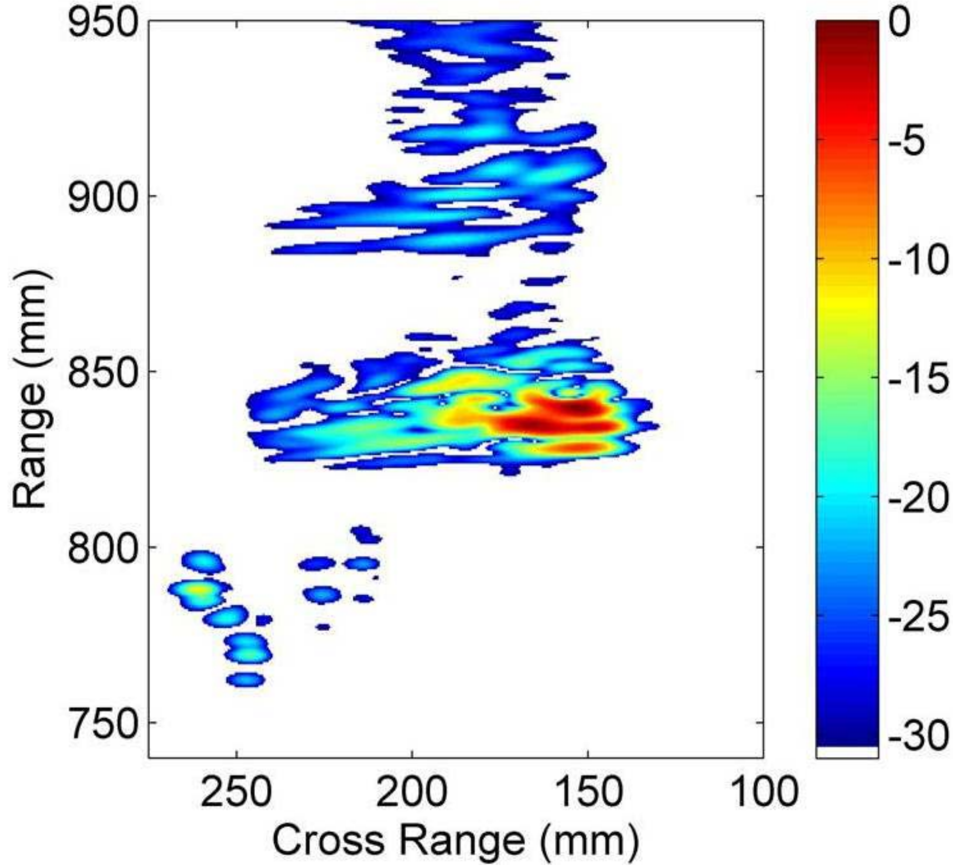

Figure 2. Synthetic aperture sonar SAS image of the backscattering by a tilted aluminum cylinder next to a free surface obtained with grazing illumination. The horizontal axis shows cross range and the vertical axis shows the range. The dynamic range is 30 dB with dark red corresponding to the strongest signal. The strongest features (the red bands) are elastic features associated with the reflection of guided waves by the cylinder's back end. Similar image features appear in NSWC pond data. The weak features on the lower left are from diffraction and weak elastic responses by the cylinder's front end. The diameter of the cylinder is 25.4 mm and the length is 127 mm.

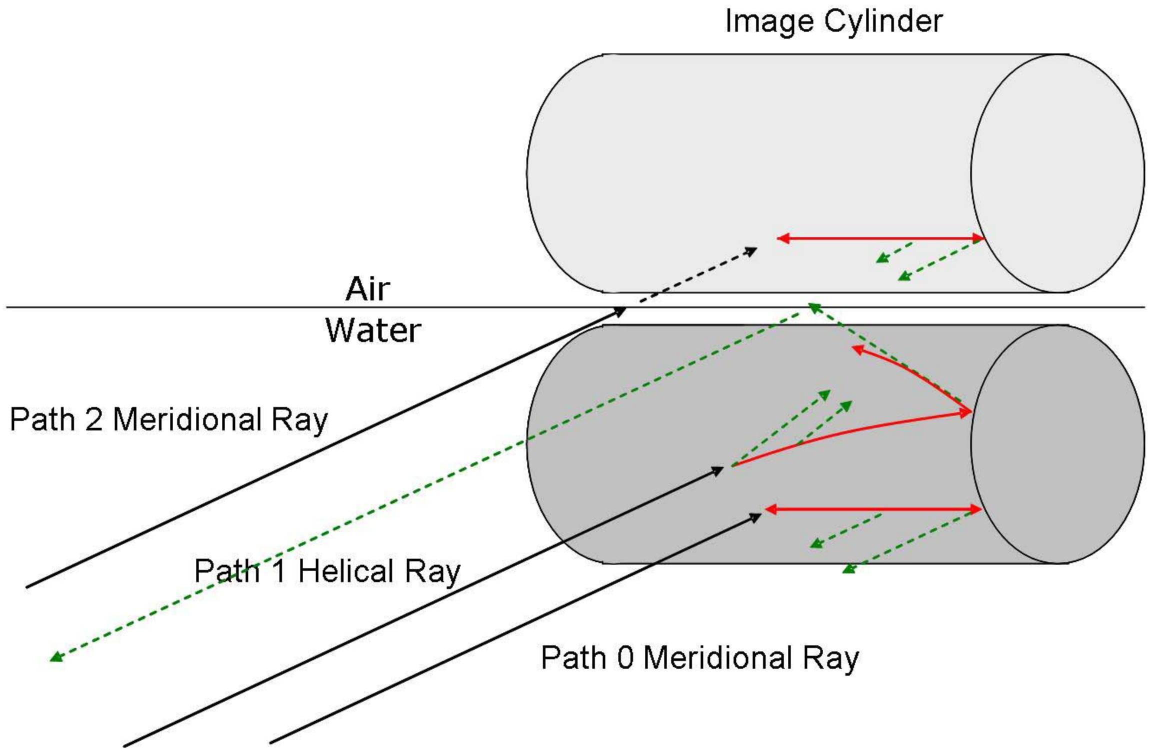

Figure 3. Ray diagram which explains the locations of the brightest three features in Figure 2. The cylinder is placed just below a free surface. The red curves correspond to elastic surface-guided rays and the green lines are rays associated with sound radiated into the surrounding water. The guided elastic Rayleigh waves reflect off of the end of the cylinder. Some of the features on the image are caused by helical Rayleigh waves on the cylinder and others are associated with meridional Rayleigh waves.

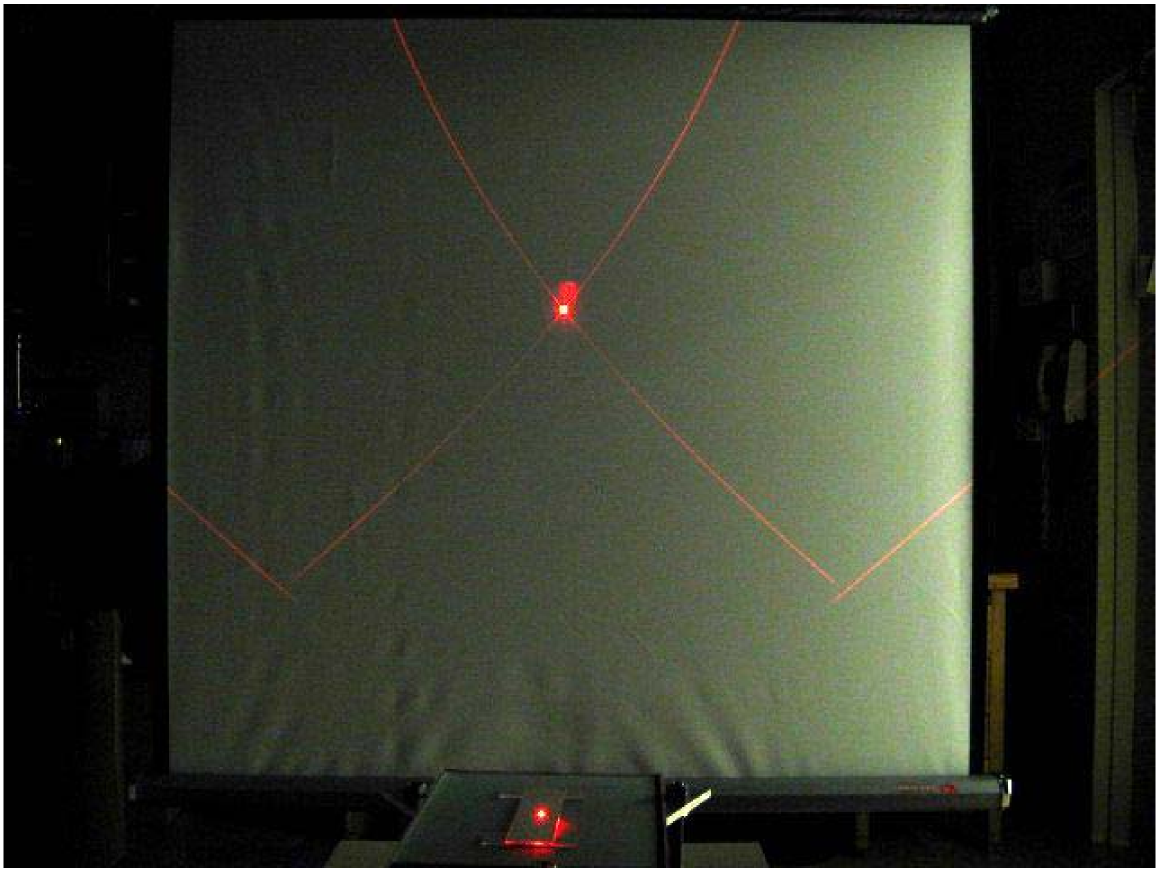

Figure 4. Example of the near-forward light scattering pattern for a small conical mirror sitting on a flat mirror. The pattern is recorded by viewing a flat screen that intersects the scattered light. The bright curves on the screen are from combinations of specular reflections that include the slanted side of the cone. The bright spot (upper center) is the direct reflection by the flat mirror. The cone is visible as the bright spot (lower center). Similar measurements for side scattering and backscattering confirm Marston's analysis of the bistatic reflection locus.

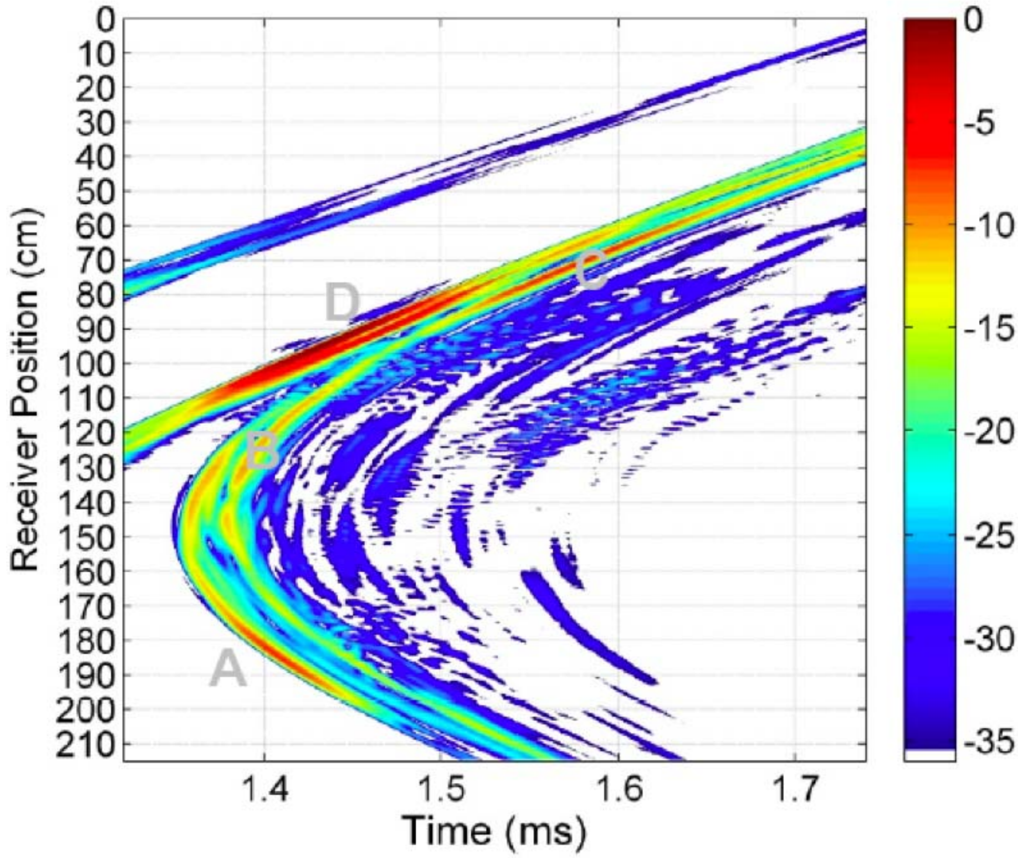

Figure 5. Acoustic detection of bistatic specular reflection from the slanted sides of an aluminum cone that penetrates the flat free surface. The grazing angle was 21.5° and the hydrophone was scanned at constant depth so as to intersect the geometric specular loci at three points. The corresponding image features are labeled by gray letters: **A** ***(for direct reflection from the side of the cone) and*** **B** ***and*** **C** ***(for cone reflections which also involve free surface interactions).*** **D** ***is a direct reflection from the flat free surface and it does not involve the cone. The dynamic range displayed is 35 dB with dark red corresponding to the strongest signal.***